Quantifying the cadence of free-living walking using event-based analysis

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Abstract: Purpose
Free-living walking occurs over a wide range of durations and intensities (cadence). Therefore, its characterisation requires a full description of the distribution of duration and cadence of these walking events. The aim was to use event-based analysis to characterise this in a population with Intermittent Claudication (IC) and a healthy matched control group.

Methods
Seven-day walking activity was recorded using the activPAL activity monitor in a group of people with IC (n=30) and an age-matched control group (n=30). The cadence, number of steps and duration of individual walking events were calculated and outcomes were derived, and compared ($p<0.05$), based on thresholds applied.

Results
Both groups had similar number of walking events per day (392+/-117 vs 415 +/-160). The control group accumulated a greater proportion of their walking at higher cadences and 32% of their steps were taken at a cadence above 100 steps/min, for the IC group this was 20%. Longer walking events had higher cadences and the IC group had fewer of these. As walking events became longer the cadence increased but the inter-event cadence variability decreased. More purposeful walking might occur at a higher cadence, and be performed at a preferred cadence. Individuals with IC had a smaller volume of walking, but these differences occurred almost entirely above a cadence of 90 steps/minute.

Conclusions
This is the first study which has quantified the cadence of continuous periods of free-living walking. The characteristics (duration, number of steps and cadence) of all the individual walking events were used to derive novel outcomes, providing new insights into free-living walking behaviour.

***4. Title Page (with authors and addresses)**

Title

Quantifying the cadence of free-living walking using event-based analysis

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Introduction

Cadence, or stepping rate, is one of the spatio-temporal properties of gait, usually reported with a unit of steps per minute. The intensity of walking has often been inferred from the cadence of the walking period. In treadmill and constrained over-ground studies, with participants walking continuously for periods of at least six minutes, a cadence of 100 steps per minute has been shown to be a good threshold for moderate physical activity [13, 16, 21].

Whilst the cadence of walking may be easily assessed over short 'test' walks it is the cadence of free-living walking that best characterises an individual's real world performance. In the free-living environment walking activity can be recorded for extended periods of time. Continuous periods of free-living walking tend to occur across a wide range of durations with periods of less than one-minute being very common in healthy individuals [1, 15].

The intensity of walking in the free-living environment has often been quantified by counting the number of steps taken within a defined time period, usually one minute. This might best be referred to as step accumulation per epoch of time, although it has been called cadence. True cadence can be defined as number of steps taken in actual time spent stepping. It has been demonstrated that step accumulation is a very different outcome measure from true cadence as walking continuously for a full minute is relatively rare [3, 19].

At present there is limited understanding of the true cadence of free-living walking. In order to understand this the true cadence of every continuous walking period must be quantified. This requires information of both the number of steps taken and the duration of the continuous walking period allowing the calculation of the average cadence for each period. This approach, focussing on the assessment of continuous periods of activity, is an event-based approach [9], and within the current work a continuous period of walking will be referred to as a walking event.

Clinical conditions may affect walking performance in a way that impacts on cadence used. One such clinical condition is peripheral arterial disease which leads to walking difficulties due to Intermittent Claudication (IC), whereby leg pain is caused by inadequate peripheral circulation. This pain leads to the person needing to stop regularly whilst walking or to limit their cadence for prolonged walking activity [5, 7, 14]. It has been shown that by monitoring an individual's free-living activity, using a body-worn activity monitor, it is possible to quantify these free-living symptoms [2, 6]. Such techniques could aid in the assessment of this condition and also quantify the effectiveness of interventions.

The full characterisation of free-living walking cadence requires a description of the distribution of several aspects. This includes the duration of events, the number of steps accumulated within these events and the cadences at which events of these durations are performed. To date, there has not been any characterisation of this either in healthy populations or those with disease. The aim of this study was to use event-based analysis to examine the cadence of free-living walking in a population with IC and a healthy matched control group.

Methods

Thirty patients with IC were recruited from a vascular out-patient clinic within NHS Forth Valley (Stirling, Scotland, UK), and thirty controls, matched for gender and age, were selected from the Glasgow Caledonian University (Glasgow, Scotland, UK) physical activity database. Data from the study, examining the broken nature of walking, have previously been reported [2].

Ethical approval was obtained from NHS Tayside B Research Ethics Committee (IC group) and from the Glasgow Caledonian University School of Health and Life Sciences Ethics Committee (control group).

Free-living activity of all participants was recorded using the activPAL^{TM} activity monitor (PAL Technologies Ltd, Glasgow, UK). This instrument is a small and unobtrusive light-weight device which is attached to the anterior aspect of the thigh [2]. The device was worn continuously to provide seven consecutive days of data.

Data from this instrument classifies activities into sedentary, standing and stride events. Consecutive stride events are combined to give walking events. The output from the instrument has been validated for classification of sedentary, upright, standing and walking activities in a range of populations including older adults [4, 8, 10, 11, 12, 17].

Data from the instrument was downloaded and a file of sedentary, standing and stride events was obtained. Using a Matlab script all walking events were extracted together with the properties of these events: start time, duration, number of steps and average cadence.

Analysis

Two approaches were taken. The first was to analyse all walking events and determine the distribution and relative contributions of these events within different cadence bands to the overall volume of walking. The second approach explored the cadence of purposeful walking. This was achieved by analysing only those events which were longer than a set duration.

Cadence across all walking events

Number of minutes spent walking within specified cadence bands

The distribution of cadence by walking event duration was calculated for each group. For each event, the number of minutes spent walking was allocated to a cadence band representing the average cadence of the event, to examine the time spent walking at each cadence band.

Proportion of steps taken above a specified cadence and the cadence below which a set percentage of steps were taken

The accumulation of walking by cadence was examined, starting at the lowest cadence and increasing to the maximum cadence accomplished. To do this all walking events were ordered by cadence, from lowest to highest. The steps taken within these events were then sequentially summed. The plot of steps taken below this specified cadence was standardised to 100% of all steps taken, to allow the proportion of steps taken below a specified cadence to be examined.

The defined outcomes were the percentage of steps taken above a set cadence (100 steps/min), and the cadence below which a set percentage of steps were taken (25%, 50% and 75% of steps).

Cadence of purposeful walking

The preceding outcome measures do not take into account the duration of the walking events. To look at 'purposeful walking' cadence outcome measures were derived using only the events above set durations. To explore the definition of purposeful walking, three duration thresholds were used (30s, 60s and 120s).

Two sets of outcomes were calculated for walking events above each of these thresholds. The first set gave an indication of the volume of activity; these were the number of walking events and the number of steps. The second set of outcomes described the cadence of the walking events. These outcomes were the mean and, to give an indicator to the inter-event cadence variability, the standard deviation of the cadence of the events.

All outcomes were calculated for each individual separately and reported as mean ± standard deviation for the population group.

Statistical analysis

Data were checked for normality by use of Kolmogorov-Smirnov tests and visual inspection of Q-Q plots. All outcomes were compared between groups using independent t-tests (SPSS statistical software). Statistical significance was set at $p<0.05$.

Results

Sample

The mean age was 67.2±9.7 years for the IC group (18M/12F) and 66.8±10.5 years for the control group (18M/12F). More detailed characteristics of the IC group are reported elsewhere [2].

Complete seven-day activity recordings were obtained from all 30 IC participants and for 28 control subjects (two wore the device for only five days). Outcomes are reported as per day.

Volume outcomes

Control participants walked for significantly more time per day (126±48 mins compared with 90±36 mins, $p=0.002$) and took significantly more steps per day (8,692±2,945 compared with 6,526±2,711, $p= 0.003$).

Cadence across all walking events

The duration of walking events was plotted against the cadence of the walking events (figure 1a) showing that for short duration events there is a wide spread of cadences but for more purposeful walking this variability decreased markedly. For longer duration walking events the number of these events is markedly reduced and the cadences of these events are in a narrower range (figure 1b).

Pooled walking events

Below 90 steps/min the distribution of cadences for both groups were similar (figure 2). However, above 90 steps/min the control group spent more minutes walking. There were also two distinct peaks in cadence for the control group, in the 70-80 and the 100-110 step/min bands. The IC group just had a single peak, in the 70-80 step/min band.

This pattern was emphasised in the accumulation curves (figure 3A). The curves had a very similar profile up to about 90 steps/min. Above this the curves diverged with the IC group accumulating far fewer steps. When the data for these curves were normalised to the total number of steps taken (figure 3B) the curve for the IC group was shifted to the left, relative to the control group, showing that overall the IC group accumulated their steps at lower cadences. These differences were significant at the 25% and 50% step thresholds, but not at the 75% step threshold (table 1). The IC group accumulated a significantly lower proportion of their steps above 100 steps/min than the control group.

Cadence of Purposeful walking

As expected as the threshold of duration for walking events included in analysis increased, both the number of walking events and steps taken decreased (table 2). At all duration thresholds, the IC group took significantly fewer steps in a smaller number of walking events. In addition, the proportion of walking events and steps which were taken above the purposeful walking threshold reduced as that threshold increased, and was significantly smaller for the IC group at all thresholds. As the duration threshold for purposeful walking events was increased, the average cadence of those events increased, while the standard deviation (i.e. variability) of the cadence reduced. Although the average cadence for the purposeful walking events was not significantly different, the inter-event cadence variability of purposeful walking for the IC group was significantly lower for the 120s duration threshold.

Discussion

Main findings and implications

This is the first study which has quantified the cadence of continuous periods of free-living walking. The characteristics (duration, number of steps and cadence) of all the individual continuous walking periods (walking events) were used to derive new outcomes. Using this approach the cadence of free-living walking behaviour can be quantified and differences between groups characterised.

The IC group walked significantly less than the control group. However, the difference between the two groups occurred almost exclusively at higher cadences. The IC group spent a lot less time (and a smaller proportion of total walking time) walking at cadences above 90 steps/minute (figure 2 and 3A).

From a health perspective this is concerning, as it implies that the difference in walking between the groups was in walking at or above moderate intensity. For meeting public health guidelines there seems to be a consensus that moderate physical activity can be represented by a stepping cadence of 100 steps/min in adults and adolescents [13, 16, 21]. In this study there was a significant difference between the groups in the proportion of steps taken above 100 steps/min, with the control group taking 33% (an average of 2,876 steps/day) of their steps above this threshold and the IC group only 20% (an average of 1,295 steps per day) (from figure 3B). However the 100 steps/min threshold has been established in healthy adults, and may not be appropriate for older adults or for people with IC.

The concept of 'purposeful walking' makes intuitive sense. We know from our own lives, that we spend time walking while performing household and work tasks at a lower cadence. However, when walking for a purpose, such as walking to the shops or train stations, or for leisure, we envisage this walking as having a longer unbroken duration, and taking place at a higher cadence. Evidence for longer duration and faster ‘purposeful walking’ in free-living activity, however, is difficult to find. A number of observational studies have reported on the cadence of walking of individuals who walked across a pre-defined area within the observational time-frame [20] demonstrating that healthy individuals do, at times, walk at cadences of 70 to 160 steps/minute.

In this study we attempted to assess purposeful walking, by analysing walking events which were longer than a set duration threshold. Although it is unclear how long such thresholds should be, by assessing three thresholds, trends in the data could be explored. It was clear that the IC group spent less time walking in longer duration events than the control group, and this difference became more marked as the duration threshold increased. The average cadence of events increased as the duration threshold increased, supporting the hypothesis that purposeful (longer) walking is generally conducted at a faster tempo. The average cadence of events increased in both groups, and the difference in the cadence of purposeful walking events was not significantly lower for the IC group. This suggests that when people with IC walk for a longer duration, they do not necessarily do so at a lower cadence. However it is clear that they spent less time walking in these longer and higher cadence events.

This analysis also showed that the cadence of free-living walking has a high degree of variability (Table 2) but that this variability decreases as the walking events get longer. Inter-event cadence variability reduced as the duration of the walking events increased and above 60 seconds cadences were mainly confined to the range of 60 to 140 steps per minute.

In this study, the control group had a greater inter-event cadence variability for these longer walking events than the IC group and this might illustrate another characteristic feature of free-living walking or a characteristic of a clinical condition. It may be that the ability to alter cadence while walking is a feature of healthy walking.

While it is clear that the people in the IC group walked less than the control group at higher cadences, it isn't clear whether this represents an inability to walk at higher cadences, or a reluctance to do so, so as not to aggravate the disease. By allocating walking events into different bands, according to the cadence of these events, we can see features in the distribution of these walking events. This analysis showed a new feature in free-living walking cadence, the two distinct peaks seen in the control group. This could indicate that the preferred cadence of everyday functional walking was lower than the cadence of more purposeful walking. The absence of this second peak in the IC group could indicate that the cadence or volume of this group's more purposeful walking was restricted by their condition. This was reflected by the results seen when analysing the cadence of purposeful walking events which showed that the proportion of longer events was smaller in the IC group.

The distribution of time spent stepping at different cadences has not been previously reported. Also this study is the first to report on the relationships between cadence and accumulation of steps and cadence and walking event length. Most previous studies examining free-living cadence have used instrumentation that has calculated step accumulation in a defined epoch. Step accumulation is equivalent to true cadence only for epochs which have only stepping. Step accumulation and true cadence are different concepts, with widely different distribution and values, but which have previously been confused [3]. This study analysed all stepping activity by considering walking events themselves, rather than minutes, irrespective of the length of the stepping event and without any artificial duration boundaries. No other study has analysed cadence in this manner. The only other study to measure true cadence in a free-living environment looked at average cadence of entire 30-minute walking periods comparing walking briskly in the park to walking briskly in an urban environment [18]. Cadence variability was higher in an urban environment due to the need of the participants to react to external stimuli, predominantly not being able to walk at their preferred cadence, and having to slow down to avoid obstacles. Low cadences may be indicative of some sort of intermittent walking activity with long pauses between steps which may, or may not, indicate that the walking event has stopped.

Although this study had a relatively small sample size it has demonstrated a new method of characterising the intensity of free-living walking. Using these methods differences could be seen, and quantified, between a clinical group and a healthy control group. The strengths of this method were the use of an instrument which could measure the duration of all walking events and provide step count and cadence for each event. A clinical group with known, but not clearly defined, walking deficits illustrated that this analysis could provide new insights into the cadence of abnormal walking behaviours.

All walking events, regardless of length of the walking event, were described by a single average cadence value. It is recognised that within each walking event, particularly the longer walking events, the cadence of walking would probably vary. Sellers et al [18] demonstrated that there was variability in cadence within a 30-minute period of walking in an urban environment, but it is unclear how this relates to individual walking events. This intra-event cadence variability would be worthy of further investigation.

Conclusions

This study demonstrates that the cadence of free-living walking, assessed analysing only continuous periods of walking (events) can be quantified in a number of ways to provide insights into the intensities of walking behaviour. For example, as the walking events became longer the average cadence increased but the inter-event cadence variability in individual free-living walking events decreased. This suggests that more purposeful walking might occur at a higher cadence, and be more usually performed at a preferred cadence compared to everyday functional activity. In this study, individuals with IC had smaller volume of walking compared to the control group, but the differences in walking occurred almost entirely above a cadence of 90 steps/minute.

Aknowledgements

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Figure legends

Figure 1 (A) Cadence of a walking event against duration of that event, for all walking events of the control group [n = 86,507]. **(B) Cadence against duration for all walking events and number of events (log scale) in these bands for the control group.** All walking events were put into defined bands. These bands were defined by cadences from 10 to 130 steps/min in increments of 10 steps per minute and by event length of duration of the event from 20s to 220s in increments of 20s. Outcomes are plotted at the lower point of each band, e.g. 20-30 steps per minute outcomes are plotted at 20 steps/min to allow visual interpretation

Figure 2 Mean minutes per day across cadence bands for all walking events for both Control and IC groups.

Figure 3 (A) Accumulation of steps for the control and IC group. The curves show the accumulation of average total number of steps per day per individual against the mean cadence of walking events. Both intermittent claudication and controls groups are plotted. **(B) Accumulation of stepping for the control and IC group**. The curves show the accumulation of the normalised total number of steps per individual against the mean cadence of walking events. Both intermittent claudication and controls groups are plotted. A 50% threshold line is plotted showing the 50% thresholds for both the control and IC groups [89 steps/min and 83 steps/min respectively].

6. Table(s)

	Controls (steps/min)	IC participants (steps/min)	*p* value
Cadence at which 25% of steps taken (Steps/min)	71.0 ± 11.2	65.7 ± 5.1	***0.020****
Cadence at which 50% of steps taken (steps/min)	88.7 ± 13.6	82.7 ± 7.9	***0.043****
Cadence at which 75% of steps taken (steps/min)	102.6 ± 13.4	96.9 ± 8.8	*0.052*
	Controls (% steps)	**IC participants (% steps)**	
% steps taken above 100 steps/min	32.4 ± 17.3	19.7 ± 13.7	***0.002****

*****$p < 0.05$ (2-tailed) *IC = Intermittent Claudication. Data are presented as mean ± 1 standard deviation.*

Table 1 *Outcome measures of cadence at specified % of steps taken and % steps of overall stepping activity taken above specified cadences for both those with IC and controls.*

6. Table(s)

		All events	'Purposeful Walking' Events included only if over duration threshold		
			Event Duration Threshold (seconds)		
		0s	**30s**	**60s**	**120s**
Number of Walking events/day in events above threshold in duration	**Controls**	391 (117)	39.9 (15.4)	14.3 (7.4)	6.1 (3.7)
	IC	415 (160)	31.5 (16.2)	8.8 (5.0)	3.1 (2.7)
	p value	*0.397*	***0.043****	***0.001****	***0.001****
% Walking events/day in events above threshold in duration	**Controls**	100	10.3 (3.1)	3.8 (1.9)	1.7 (1.1)
	IC	100	7.6 (2.7)	2.2 (1.2)	0.8 (0.8)
	p value	-	***0.000****	***0.000****	***0.001****
Number of Steps/day in events above threshold in duration	**Controls**	8,692 (2,945)	5,313 (2,517)	3,980 (2,198)	2,978 (1,849)
	IC	6,526 (2,711)	3,048 (1,622)	1,938 (1,370)	1,269 (1,165)
	p value	***0.003****	***0.000****	***0.000****	***0.000****
% Steps/day in events above threshold in duration	**Controls**	100	58.1 (14.3)	42.6 (16.1)	31.4 (15.3)
	IC	100	44.5 (12.3)	27.7 (14.9)	17.7 (14.3)
	p value	-	***0.000****	***0.000****	***0.001****
Average Cadence of events above threshold in duration	**Controls**	68.4 (5.7)	80.7 (10.0)	92.3 (11.4)	102 (9.5)
	IC	68.2 (5.6)	78.3 (5.8)	91.5 (8.2)	97.8 (10.4)
	p value	*0.753*	*0.251*	*0.765*	*0.111*
Inter-event cadence variability (standard deviation) of events above threshold in duration	**Controls**	25.2 (2.6)	18.6 (3.2)	16.4 (4.5)	12.9 (6.0)
	IC	25.0 (5.1)	18.1 (3.9)	14.3 (4.0)	8.5 (3.7)
	p value	*0.881*	*0.619*	*0.062*	***0.002****

IC = participants with IC. Data are presented as mean ± 1 standard deviation.

Table 2 Outcomes for events above set duration thresholds for both *participants with intermittent claudication and for controls. Results show the mean and standard deviations of the outcomes obtained for each group calculated from individual outcomes. Inter-event cadence variability is the standard deviation of the cadences for each individual, the results in the table for this variable are therefore the mean and standard deviations of these standard deviations.*

7. Figure(s)
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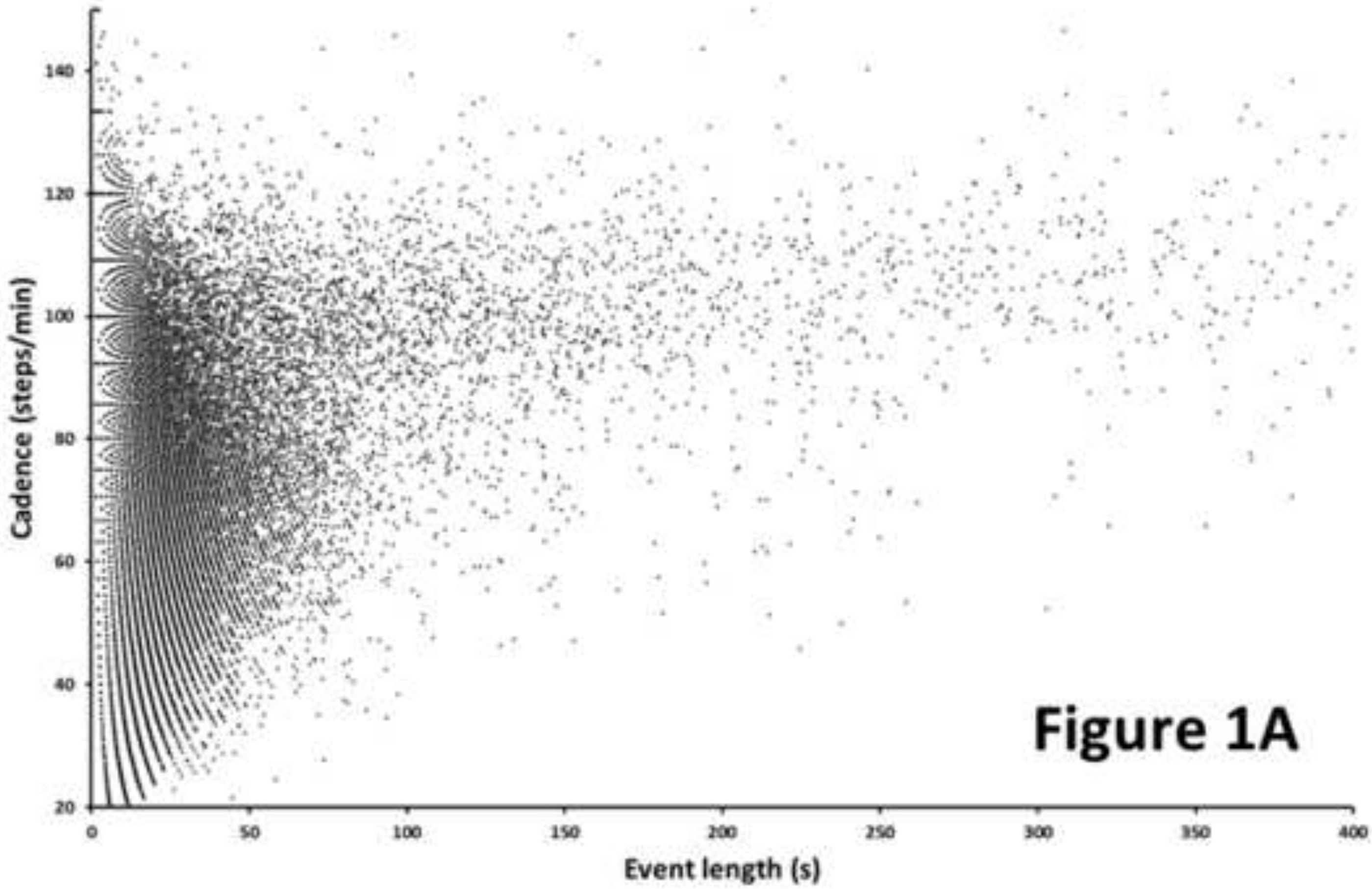

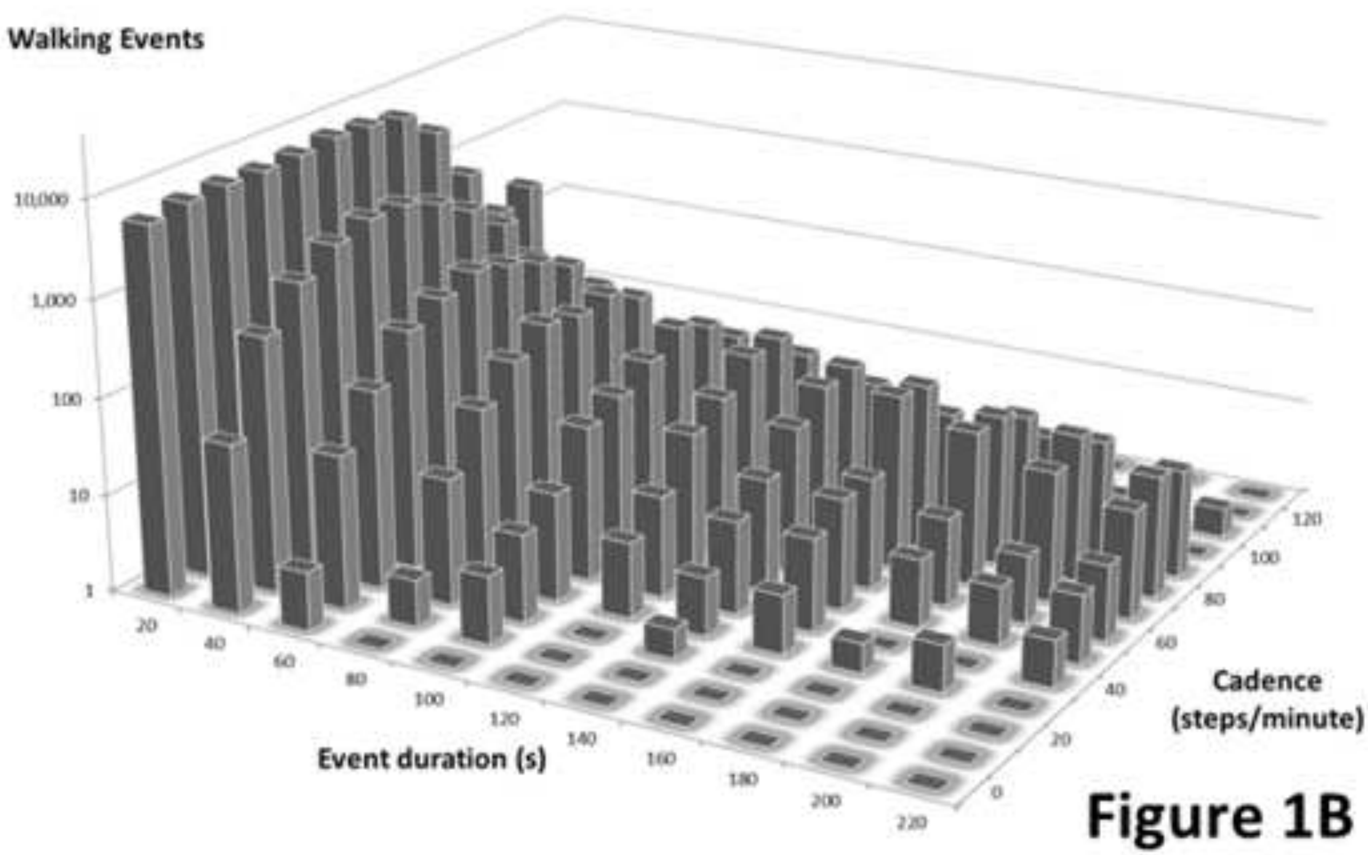

Figure 2
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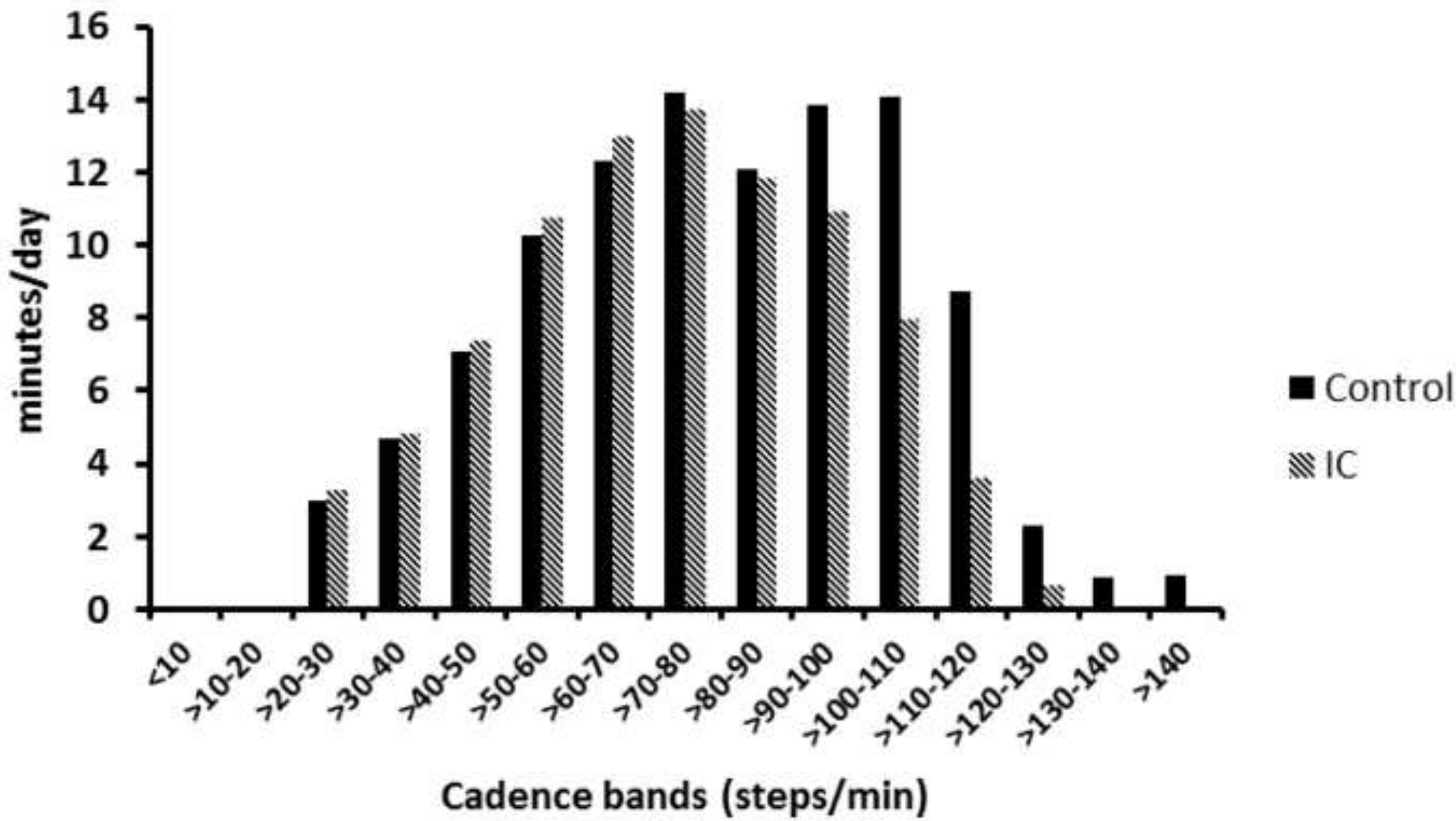

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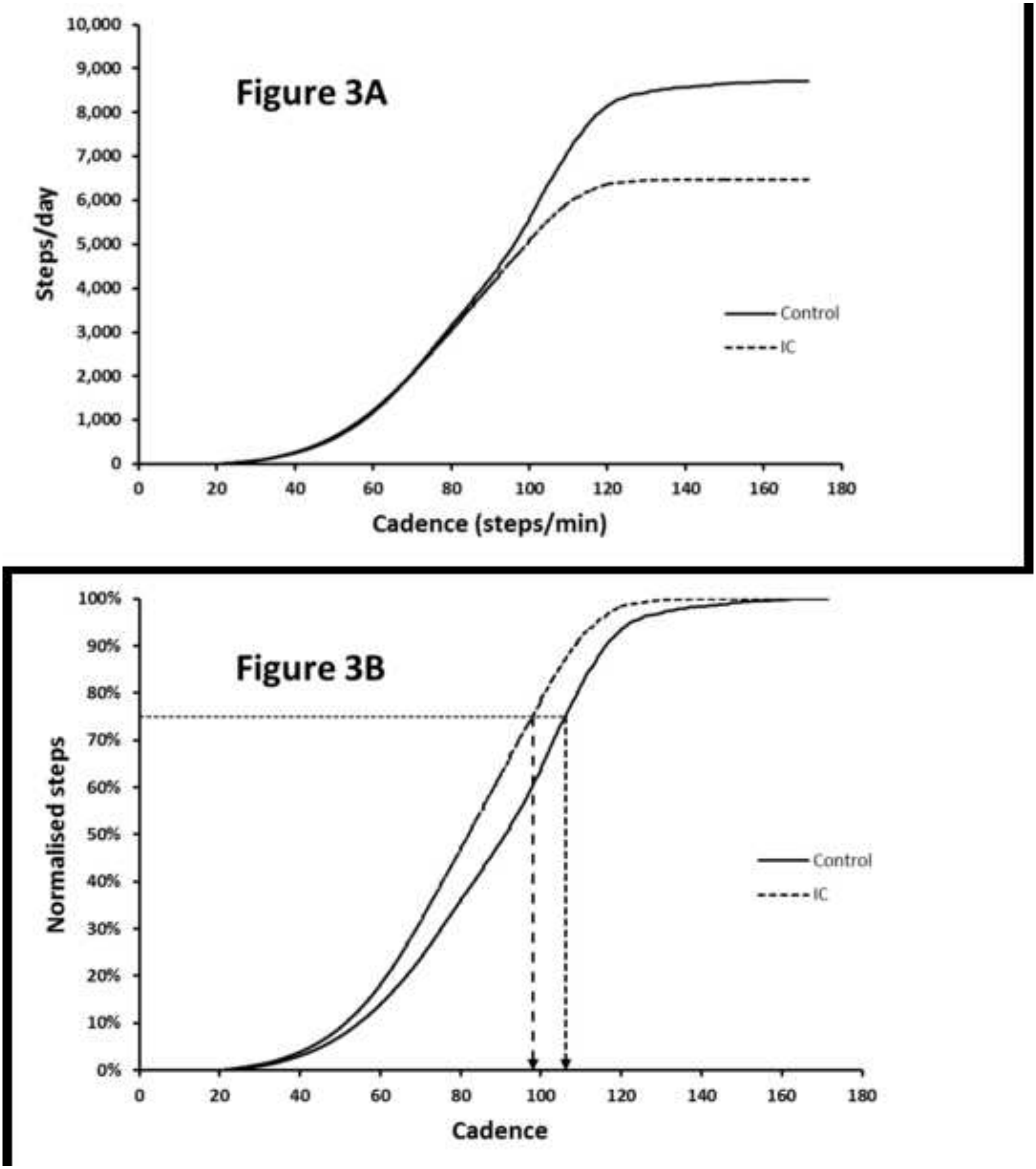

***Research Highligts**

Using event-based analysis outcomes for cadence of free-living walking were proposed

Continuous seven day recordings were made on both a clinical and a healthy population

Differences between groups in the cadence of free-living walking were characterised

Longer walking periods occur at a higher cadence and performed at a preferred cadence

People with Intermittent Claudication walk for less above a cadence of 90 steps/min